

On the masses of the components of the V1387 Aql/GRS1915+105 binary system

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ABSTRACT

V1387 Aql (the optical companion to the microquasar GRS1915+105) is a low mass giant. Such star consists of a degenerate, nearly isothermal helium core and a hydrogen rich envelope. Both components are separated by an hydrogen burning shell. The structure of such an object is relatively simple and easy to model. Making use of the observational values of the luminosity and of the radius of V1387 Aql, we determined the mass of this star as equal $0.28 \pm 0.02 M_{\odot}$. This determination is relatively precise thanks to high sensitivity of the luminosity of such structure to the mass of the helium core and high sensitivity of its radius to the mass of the envelope. The estimate does not depend on the knowledge of the distance to the system (which is not precisely known). The main source of the uncertainty of our estimate is uncertainty of the effective temperature of V1387 Aql. When the effective temperature will be known more accurately, the mass of V1387 Aql could be determined even more precisely.

Key words: binaries: general – stars: evolution – stars: individual: V1387 Aql – stars: low mass – X-rays: binaries – X-rays: individual: GRS1915+105.

1 INTRODUCTION

GRS1915+105 is a low mass X-ray binary known also as one of the most distinct Galactic microquasars (Mirabel & Rodriguez 1994). The system contains a black hole and a low mass K0-3 III optical companion (Greiner et al. 2001). The companion which got a variable star name V1387 Aql fills its Roche lobe and supplies the matter accreted by the black hole. The first determination of the masses of the components by Greiner et al. (2001) indicated that the system contains one of the most massive galactic binary black holes with the mass $14 \pm 4 M_{\odot}$. This mass estimate was sensitive to the distance to the system which was estimated from the kinematics of the jets as 11–12 kpc (Mirabel & Rodriguez 1994, Fender et al. 1999). After successful radio parallax measurement by Reid et al. (2014) the distance was decreased to $8.6^{+2.0}_{-1.6}$ kpc and the revised mass of black hole to $12.4^{+2.0}_{-1.8} M_{\odot}$. This new distance determination is consistent with independent estimate of $\lesssim 10$ kpc by Zdziarski (2014) based on considering the jets kinetic power.

Since the orbital period of the system is quite long (33.85 d), the Roche lobe filling component must have large radius and cannot be a main sequence star but rather an evolved giant (as indicated also by the spectral luminosity class). The structure of such low mass giant is relatively simple and easy to model. Making use of the observational values of the luminosity and of the radius of V1387 Aql, we will construct the model of this star and determine relatively precisely (with the accuracy of $\sim 7\%$) its mass. This pa-

rameter was until now very poorly constrained (Fragos & McClintock (2015) gave the range (0.1–0.9 M_{\odot}).

2 OBSERVATIONAL PARAMETERS OF V1387 AQL

We will make use of very well known value of the orbital period of the system ($P = 33.85 \pm 0.16$ d, Steeghs et al. 2013), less well known mass of the black hole component ($M_X = 12.4^{+2.0}_{-1.8} M_{\odot}$, Reid et al. 2014) and the least well known value of the effective temperature of V1387 Aql ($T_e = 4100\text{--}5433$ K, Fragos & McClintock 2015). These parameters will be used to estimate the radius and the luminosity of V1387 Aql.

From third Kepler law we have,

$$A/R_{\odot} = 4.208(M/M_{\odot}(P/1d)^2)^{1/3} \quad (1)$$

where A is the separation of the components, $M = M_X + M_{\text{opt}}$ is the total mass of the binary system and P is its orbital period.

The relation between the radius of the optical component (which must be equal to the radius of its Roche lobe) and the separation of the components is (Paczynski 1971),

$$R_{\text{opt}} = 0.462A(M_{\text{opt}}/M)^{1/3} \quad (2)$$

where M_{opt} is the mass of the optical component.

From eqs. (1)–(2) we have,

$$R_{\text{opt}}/R_{\odot} = 1.944(P/1d)^{2/3}(M_{\text{opt}}/M_{\odot})^{1/3} \quad (3)$$

From preliminary calculations we know that $M_{\text{opt}}/M_{\odot} \approx 0.28$

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(the consecutive improvements of values of R_{opt} and M_{opt} may be considered as quickly convergent iterative process). Inserting this value and value for the orbital period into eq. (3) we get $R_{\text{opt}}/R_{\odot} = 13.31$. The precision of this determination is $\sim 2\%$ (it is related to the error of about 7% in M_{opt}).

Our radius estimate does not depend on the distance to the binary system. However, having a relatively very precise radius estimate, we may obtain a yet another estimate of the distance to the system. We may use the observed angular diameter of the optical component. The value of this diameter was estimated by Zdziarski et al. (2005) from the K band flux as equal $s = 0.0175\text{--}0.0220$ mas. This value together with our value of R_{opt} translates into the distance 5.6–7.1 kpc. This range is marginally consistent with the distance derived from the radio parallax by Reid et al. (2014).

To estimate the luminosity of V1387 Aql one needs to know its effective temperature. It may be estimated from the spectral type of the star: K0III–K3III (Fragos & McClintock 2015). We will follow the procedure of Fragos & McClintock which was based on calibrations tabulated by Gray (2008) and Cox (2000). This approach leads to rather wide range of effective temperatures: 4100 to 5433 K with the mean value of 4766 K (if one uses only Cox tables, the range is much narrower: 4280 to 4660 K). The mean value of the temperature together with the earlier determination of the radius leads to the luminosity of $81.9 L_{\odot}$ with the uncertainty range of 45 to $138 L_{\odot}$ (if one uses only Cox tables, the range is 53 to $75 L_{\odot}$).

3 THE MODEL OF V1387 AQL

The structure of low mass giant such as V1387 Aql is rather simple. It contains a degenerate, nearly isothermal helium core surrounded by a thin hydrogen burning shell. Above the shell there is a hydrogen rich envelope. Its mass might be different for different giants: it could be less than $10^{-2} M_{\odot}$ (as is the case for V1387 Aql) but could be also several times greater than the mass of the helium core. The luminosity generated by the hydrogen shell (and so the luminosity of the giant) depends practically only on the mass of the core. This relation (noted first by Paczyński 1970) is very well defined. This fact is demonstrated in Fig. 1. One may notice that the luminosity depends slightly also on the mass of the envelope but this dependence is very weak: Fig. 1 shows that increasing the mass of the envelope by a factor of 200, changes the luminosity only by about 20 percent. I should comment on the fact that the red curve was computed only for a relatively narrow range of the helium core masses. This was due to the reasons of the computational convenience: it was necessary to keep the very low mass of the envelope while substantially changing the mass of the underlying core. To summarize these considerations: the luminosity of a giant translates directly into the mass of its helium core.

On the other hand, the radius of a giant depends mainly on its luminosity (the effective temperature does not change very significantly during this phase of the evolution) and so again mainly on the mass of the core. The dependence on the mass of the envelope is weak. This situation changes dramatically when the mass of the envelope drops below about $10^{-2} M_{\odot}$: the radius becomes a very sensitive function of the envelope mass. This is well demonstrated in Fig. 2. If the star is in this evolutionary phase, we can precisely determine the mass of the envelope from the radius of the star.

We constructed models reproducing the present state of V1387 Aql using the Warsaw evolutionary code described by Ziółkowski (2005). The standard Population I chemical composition of $X = 0.7$ and $Z = 0.02$ was adopted as the initial chemical composition.

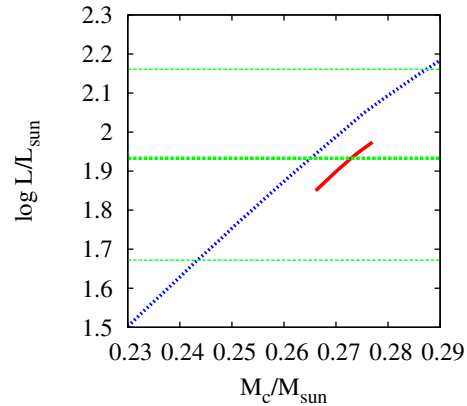


Figure 1. The core mass-luminosity relation for models approximating the present evolutionary state of V1387 Aql. The lower (red) curve describes models with the envelope mass equal about $6.5 \times 10^{-3} M_{\odot}$ (corresponding to the value for V1387 Aql). The upper (blue) curve describes models with the envelope mass equal about $1.25 M_{\odot}$ (200 times larger). The thick horizontal (green) line corresponds to the present luminosity of V1387 Aql and thin horizontal lines correspond to the uncertainties of this parameter.

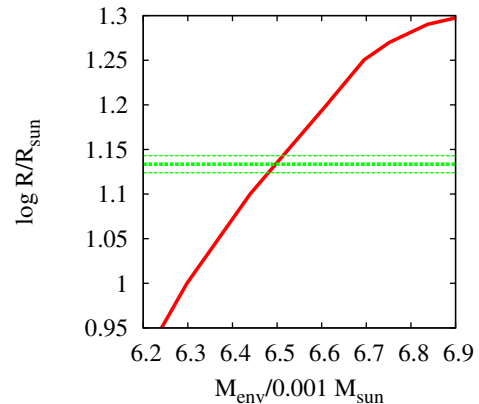


Figure 2. The envelope mass-stellar radius relation for models approximating the present evolutionary state of V1387 Aql. The thick horizontal (green) line corresponds to the present radius of V1387 Aql and thin horizontal lines correspond to the uncertainties of this parameter.

No convective overshooting was taken into account. The results are summarized in Figs. 1–3. From Fig. 1 we can read the present mass of the helium core of V1387 Aql as $0.273 \pm 0.02 M_{\odot}$. The uncertainty of this determination was estimated from the upper (blue) line in Fig. 1. Please, note that the dependence of the luminosity on the core mass is so strong that in spite of the large error of luminosity estimate (uncertainty by a factor of about three) we still got quite precise (error of about 7%) determination of the core mass. In a similar way, Fig. 2 permits the determination of the mass of the envelope of V1387 Aql as $\sim 6.5 \times 10^{-3} M_{\odot}$. Together with the mass of the core it gives the present mass of V1387 Aql as $0.28 \pm 0.02 M_{\odot}$. Note that this estimate is much more precise than the range $0.1\text{--}0.9 M_{\odot}$ quoted by Fragos & McClintock (2015).

The internal structure of V1387 Aql is illustrated in Fig. 3. One may see that indeed the core is nearly isothermal. I may add that the degeneracy parameter of the electron gas $\psi = E_{\text{Fermi}}/kT$ is

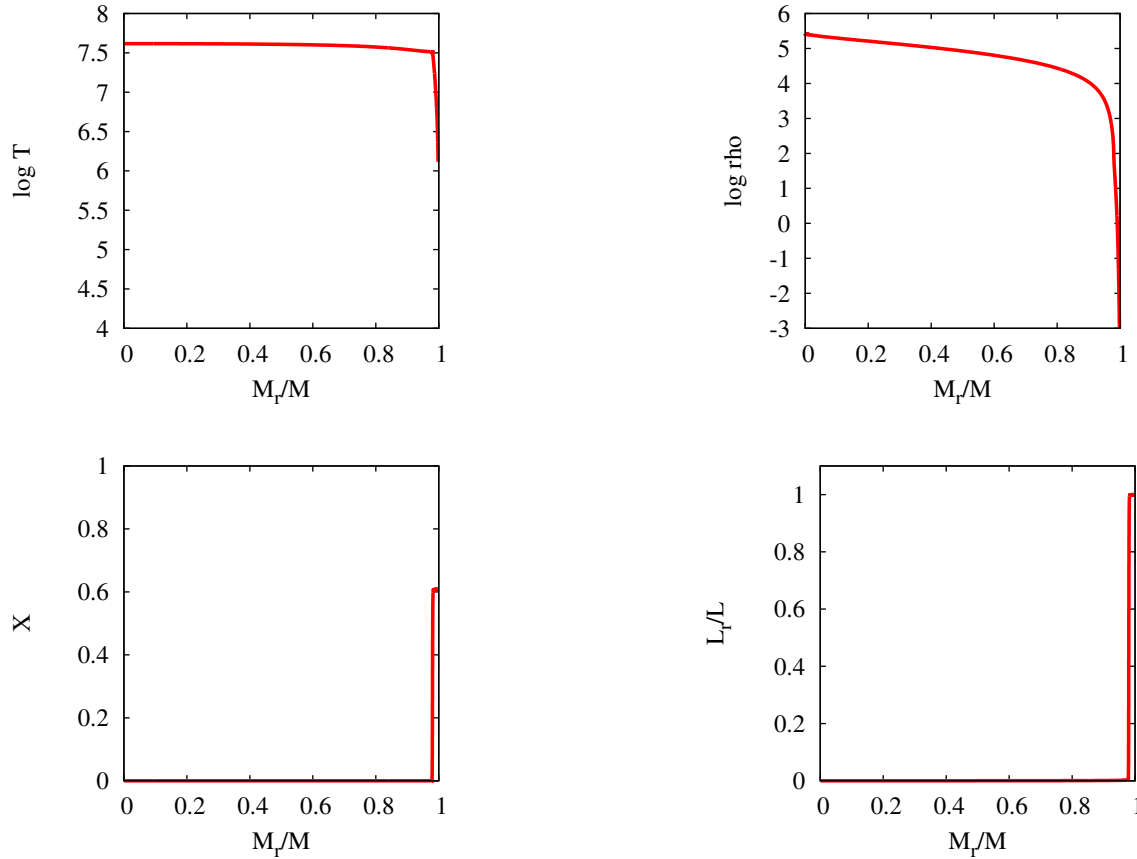


Figure 3. The internal structure of the model describing the present evolutionary state of V1387 Aql: (a) the temperature distribution, (b) the density distribution, (c) the hydrogen content profile and (d) the distribution of the ratio of luminosity L_r generated inside the radius r to the total luminosity L .

about 18.7 in the center of the star. It means that the electron gas pressure and internal energy are by a factor of about 7.5 larger than computed under the ideal gas approximation.

One comment that should be made concerns the luminosity of a star losing mass through Roche lobe overflow. If the mass outflow is very rapid, the surface luminosity of the star might be significantly lower than in the case of no outflow. It is known that V1387 Aql is losing mass to the black hole companion, occasionally at black hole Eddington rate ($\sim 10^{-7} M_\odot/\text{yr}$). However, this rate is not high enough to decrease substantially the surface luminosity of the star.

4 THE MASS AND THE ORIGIN OF THE SPIN OF BLACK HOLE

Unfortunately, the precise knowledge of the mass of the optical component does not help to improve the accuracy of the black hole mass determination. It would be possible if we knew the components mass ratio precisely enough. Unfortunately, at present, the error of the mass ratio determination is rather large: $q = M_{\text{opt}}/M_X = 0.042 \pm 0.024$ (Steeghs et al. 2013). This determination is based on the rotational broadening of V1387 Aql absorption lines. There is no hope that the precision of this measurement will improve substantially in near future.

The present structure of V1387 Aql has no memory of its past evolution. It could achieve the present state starting from different

initial configurations. Fragos & McClintock (2015) suggested that this initial configuration could be a star as massive as $5 M_\odot$. The large amount of the mass from the donor accreted by black hole would then help to explain its large spin. It cannot be excluded that V1387 Aql originated from the star of the initial mass about $5 M_\odot$. However, arriving at the present configuration would require a rather fine tuning of its mass loss history. It would have to be large during the initial phase of the evolution to avoid the development of too large helium core.

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